



AFRL-RQ-ED-TR-2016-0010

Ignition of Propellants Through Nanostructured Materials

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March 2016

In-House Final Report

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
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1. REPORT DATE (MM/DD/YYYY) 3/31/2016		2. REPORT TYPE In-House Final Report		3. DATES COVERED (From - To) 4/1/2008 - 1/1/2016	
4. TITLE AND SUBTITLE Ignition of Propellants Through Nanostructured Materials			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 62102F		
6. AUTHOR(S) Stephen Danczyk; Malissa Lightfoot; Alireza Badakhshan (ERC)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER Q0BL		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RQRC 4 Draco Drive Edwards AFB CA 93524-7160			8. PERFORMING ORGANIZATION REPORT NO.		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RQR 5 Pollux Drive Edwards AFB CA 93524-7048			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RQ-ED-TR-2016-0010		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES PA Clearance #: 16289					
14. ABSTRACT <p>This project was started with the intention of utilizing ignition properties of nanoparticles and nano-energetics for ignition of fuel spray. There are a number of properties that are desirable for an ignition system. Ideally an ignition system should be robust, efficient, reliable, simple, low cost, and flexible. Also, an ignition system should initiate combustion under a broad range of conditions in order to maximize the operational flexibility of energy and propulsion systems.</p> <p>We have studied the ignition of liquid fuel and simulated solid rocket fuels by the photo-ignition of single wall carbon nanotubes. The investigation includes the effect of solid additives such as aluminum nano-particles and solid oxidizers such as ammonium perchlorate on the photo-ignition characteristics. We found that by mixing carbon nanotubes with other nanoparticles and powdered material, the ignition parameters such as; burn temperature and burn duration can be tailored to meet different ignition requirements such as ignition energy, ignition delay, pressure, temperature, and burn duration. We also studied photo-ignition of liquid fuel by graphene oxide. We believe our study of photo-ignition of a fuel spray and a solid fuel provides a suitable method for ignition of liquid rocket engines and solid rocket motors. Among the advantages of this approach are a compact, light-weight, and robust ignition method and it enables volumetric distributed ignition of fuel sprays.</p>					
15. SUBJECT TERMS Ignition system; photo-ignition; high pressure ignition torch; carbon nanotubes; nanoparticles; graphene oxide foams					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Stephen Danczyk
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NO (include area code) 661 275-6208

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1.0 SUMMARY

The objective of this work was to utilize the ignition properties of nanoparticles and nano-energetics for the ignition of a fuel spray. We believed that we could improve the robustness, simplicity, flexibility and cost of the igniter while also minimizing the energy needed for its initiation. Through this program, we have developed greater insight into the properties needed in a photoignitable material, and we have demonstrated an improved igniter system based on these insights. We have a patent pending on this technology [1].

Our investigation started with the investigation of what nanoparticles were photoignitable and the necessary properties of the initiating light source were. We found that iron (Fe) nanoparticles played a key role in the ignition of single-walled carbon nanotubes (SWCNT), but there are other materials that exhibit photoignition without iron nanoparticles, materials such as graphene oxide foams and porous silicon. We also found that the wavelength of the light source had little impact on the ignition, and we quantified the minimum ignition energy for several materials.

Using this knowledge, we moved on to demonstrate ignition of a liquid spray for methanol, acetone, hexane and RP-1. We discovered that the SWCNT material does not ignite well if wet, so we encapsulated the material to protect it from the fuel spray. To improve the robustness of the system, we examined placing different mixtures of fuels and oxidizers in the capsule with the carbon nanotubes (CNTs). By tailoring these mixtures, we were able to develop reliable ignition capsules that operated at pressures up to ~50 atm. During this part of the study, we were also able to demonstrate ignition of solid rocket propellant using photoignitable CNTs.

At the conclusion of this work, we combined our knowledge to develop the high pressure PhotoIgnition TorCH (PITCH). This device provides a suitable method for ignition of liquid rocket engines and solid rocket motors. Among the advantages of this approach are a compact, light-weight, and robust ignition method and it enables volumetric distributed ignition of fuel sprays.

2.0 INTRODUCTION

Ajayan et al. first reported the photoignition of SWCNTs by a camera flash in 2002 [2]. It was suggested that Fe nanoparticles within SWCNTs play an important role in the photoignition process [3]. We studied the effects of SWCNT production methods on photoignition and reproduced some of the aforementioned results [4-7]. We extended the study of photoignition of SWCNT to consider other effects such as light source properties and compaction of the material. Photoignition of graphene oxide (GO) for fuel ignition applications has also been demonstrated [8]. We have studied several other nano-materials to examine the possibility of igniting them with a camera flash.

The photoignition results prompted us to look at this as a possible new approach for the initiation of combustion in propulsion systems. We suggested that SWCNTs could be used as an ignition agent for a variety of fuels, including those of interest in liquid rocket engines [5-7]. Other applications of photoignition of SWCNTs have also been reported [9-11]. More recently, research on the photoignition of gaseous fuel and air mixtures showed distributed ignition [12, 13]. The general approach in all of these reports is to take advantage of the exothermic decomposition of carbon nanotubes to initiate combustion with reactants mixed with the nanotubes. Our approach goes beyond the general practice and involves an ignition capsule that

holds a photo-ignitable solid fuel mixture (SFM) separate from the fuel so that it is protected from getting wet by the fuel spray. The capsule is designed so that it discharges a stream of burning particles into the combustion zone to create a volumetric ignition, referred to as an ignition torch. We have extended this approach to work as a high pressure ignition torch that is capable of fuel ignition up to 135 atm (~2000 psi); to accomplish this feat, the capsule must contain a variety of components beyond the photoignitable SWCNT. We have formulated different CNT-based photo-ignitable solid fuel mixtures for ignition at different pressures. Finally, we have extended this work to consider the ignition of solid fuels.

There are a number of properties that are desirable for an ignition system. Ideally an ignition system should be robust, efficient, reliable, simple, low cost, and flexible. Also, an ignition system should initiate combustion under a broad range of conditions in order to maximize the operational flexibility of energy and propulsion systems.

This program considered five main series of experiments, and the presentation of methods and results is broken into subsections corresponding to these areas. As presented briefly above, we have considered (1) the effect of nanotube production method on photoignition of SWCNTs, (2) the effect of the light properties on the photoignition of SWCNTs, (3) the photoignition of materials other than SWCNTs, (4) ignition of fuel sprays, and (5) examination of SFMs to extend the ignition envelope. The conclusions and recommendations summarize the entire body of work from all of these experimental investigations. The overall goal of this work was to provide a new ignition method for rocket applications which utilized the photoignition property of SWCNTs; we have successfully developed and demonstrated a compact, robust and stable igniter that is initiated via a camera (or similar) Xenon (Xe)-arc flash.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Effect of Production Method

We studied ignition characteristics of SWCNTs as a function of their iron concentration [5, 6]. Two different sets of samples of as-produced, i.e. unpurified SWCNTs, were obtained from two different vendors, each produced by a different growth method. For most applications SWCNT samples need to be purified through multiple steps of chemical treatment in order to decrease the concentration of impurities, mostly iron nanoparticles and amorphous carbon, in the sample and increase the concentration of carbon nanotubes. However, we used as-produced SWCNT samples because they show photoignition effect with substantially lower photon energy. We will refer to the unpurified samples (with typical impurity of > 50% by weight) as carbon nanotube (CNT) samples in order to deemphasize the single wall content of the sample. Based on our experience samples with high concentration of SWCNT (>90%) do not exhibit photoignition effect [6].

One set of samples utilized is similar to that used by Chehroudi [5] and Smits [10], and is produced by Unidym Inc. utilizing the high pressure carbon monoxide (HipCo) method, with Fe nanoparticles as a catalyst. The second set of samples were purchased from Sigma Aldrich and is produced via a plasma arc method with nickel and yttrium catalyst particles, similar to a sample mentioned by Ajayan [2]. We also purchased samples that were produced by HipCo method with a wide range of Fe concentrations (3-51% by weight).

All of these samples were exposed to a Xe-arc camera flash with a flash duration on the order of 1 ms. In each case the exposure to the flash was observed by eye for evidence of

ignition, which is indicated by transformation of some iron nanoparticles to visible clusters of orange iron oxide.

3.2 Effect of Light Source and Compaction

This series of experiments included investigation of potential correlations between the properties of the flash (light source) and the photoignition phenomenon as well as considering if compaction of the sample altered the photoignition reaction [5]. Specific properties of the light source under consideration were optical fluence, flash pulse duration, wavelength of the light and optical spectral span. By studying the effect of compaction force on ignition, we hoped to better understand the interaction of the light with the nanomaterial.

The basic experimental setup (Figure 1) consists of an ignition light source, either a Vivitar or a Canon camera flash (model number 730AFN and 580 XE II, respectively), a pulse energy meter (GenTec, SUN series EM-1 with ED-500 detector head), a sensitive microphone (Piezotronic Inc. model S05692) for detection of any photo-acoustic signal, and an XYZ traversing stage with a filter wheel for introducing optical filters within the light path. The pulsed light source (i.e., Xe-arc camera flash), with 0.1 and 7 ms durations at low and high light-energy settings, was coupled to the sample area through a 3'x1/2" quartz fiber optic light guide from Sunoptics Technologies. In most cases a fuel spray was produced at room temperature by an ultrasonic atomizer from Sono-tek Corp., model 8700-25.

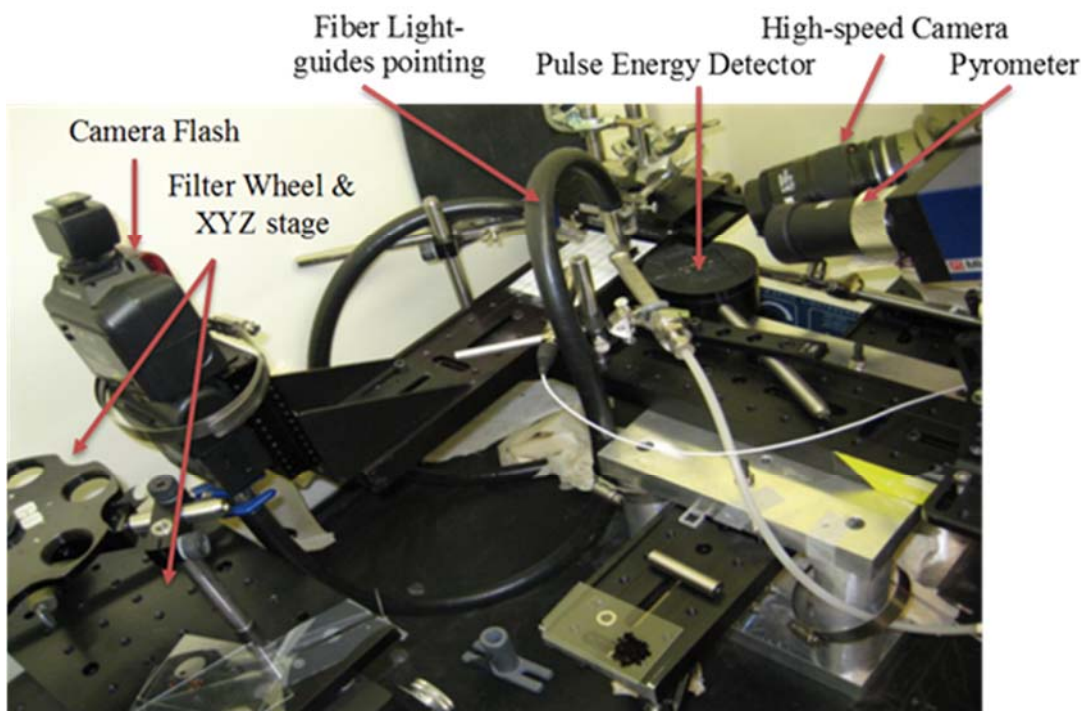


Figure 1: The Experimental Setup for the Study of Photoignition Effect in SWCNT
Digital camera and the fiber coupling for the spectrometer are not shown.

As-produced samples of CNT with ~50% Fe content (by weight) were used for this study. These are similar to the high Fe content Unidym samples described in Sections 3.1 and 4.1. These samples are “fluffy” in appearance and easily fluidized in air. For compacted samples a ball of the fluffy sample with a nominal diameter of ~ 2-cm was placed between two glass slides and known weight was gently placed on the top slide in order to achieve a thick film of CNT with a certain level of compaction.

During both the light-property and compaction experiments, the energy per pulse was increased progressively from a very low value to a higher value by moving the sample and light source closer to one another until a sudden (and distributed) ignition at multiple locations was observed. The flash pulse energy on the sample at this point is considered the minimum ignition energy (MIE) needed for the ignition of CNT samples.

3.3 Photoignition beyond CNTs

We studied ignition characteristics of CNTs and a number of other nanoparticles or nanostructured materials in order to identify those parameters that are particularly useful in photoignition process [14]. We achieved consistent results with CNTs, GO foam, aluminum nanoparticles (Al₂O₃ NP), carbon coated iron, iron powder and palladium (Pd) powder. We also studied the photoignition properties of carbon-based materials such as multi-walled CNTs, C60 fullerenes and carbon black, as well as metallic and nonmetallic fine particles, and ball milled metallic thermites. The ignition characteristic of interest is the MIE. As in the Section 3.2 experiments, MIE was established by traversing the Xe-flash light source closer to the sample through an optical fiber bundle (ID=12 mm and L= 1m) as a light coupling medium, until sudden and distributed ignition was observed.

Due to interesting results with GO, additional investigations were undertaken with this material [8]. The GO foams were created by freeze-drying GO dispersions at a variety of concentrations. A porous structure results from the drawing off of water without causing collapse of the solid matrix of GO platelets due to capillary action, as would happen with conventional evaporation. The GO samples were ignited in unconfined air and in a glass vessel that had an argon (Ar) environment or had been evacuated. The camera flash was located outside of the vessel. A high-speed Phantom V7.1 camera from Vision Research Inc. was used in order to track the regression of the reaction front [8].

3.4 Ignition of Fuel Sprays

The fuel burning study included demonstration and visualization of the fuel ignition process by photoignition [14]. The hardware for the photoignition light source is shown in Figure 2. We ignited RP-1 sprays produced with an ultrasonic atomizer from Sono-tek model 8700-25, shown in Figure 3. The atomizer was modified to produce swirl action in its gas outlet in order to achieve a more uniform spray and a better air/gas and fuel mixing. We rapidly determined that the CNTs needed to be kept dry. To accomplish this separation, CNTs were encapsulated by placing them in a transparent gelcap container 0.75 cm³ in volume (D=7 mm L=20 mm), that is referred to as an ignition capsule. The ignition capsule and its placement with respect to the light source is shown in Figure 2. The two part capsule that was used in this study typically ruptured around 30 psi.

Two different setups were utilized for the fuel ignition experiments. The first one was used for observation of the dynamics of the photoignition process at atmospheric pressure with an unhindered view of the ignition source and the ignition process. Figure 4 shows the second

fuel ignition setup, a mid-pressure test chamber that was utilized to observe ignition up to ~30 atm. The chamber's pressurizing gas was air, or a combination of nitrogen and air for reduced oxidation capability. Results include both stagnant and flowing-gas conditions. The liquid flow was 1-3 ml/min and the gas flow was not measured.

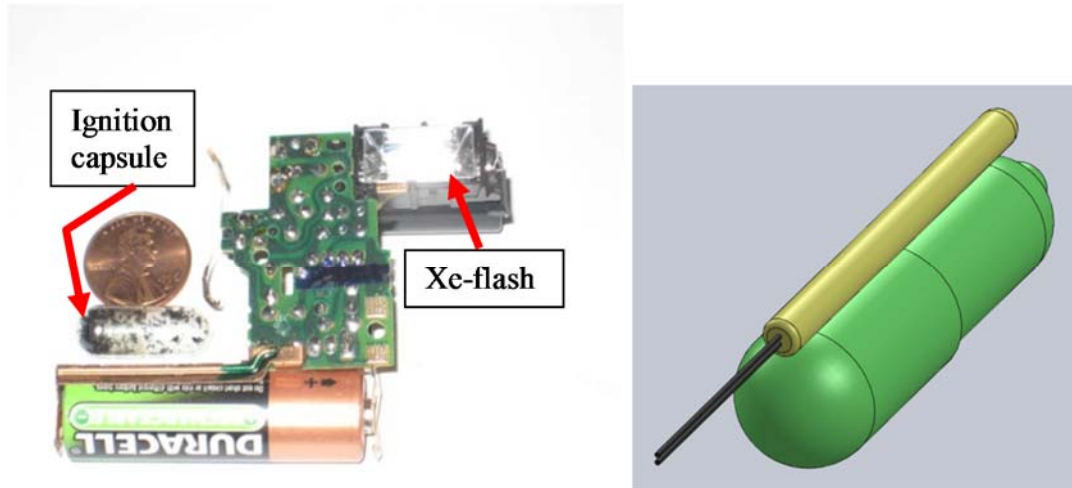


Figure 2: Complete Hardware of a Self-contained Photoignition Device

The photographic image of the completed hardware of a self-contained photoignition device that was used in most of the reported ignition systems and torches. The ignition capsule that is shown below the penny is 5-10% filled with 30-70 mg of the nanostructured solid fuel mixture. Normally the capsule is placed alongside of the Xe-flash that is shown at the top right where it receives the maximum exposure.



Figure 3: Customized Ultrasonic Atomizer (OD=6 cm)

The customized ultrasonic atomizer (OD=6 cm) that was used as the fuel injector at atmospheric pressure and at an intermediate pressure up to about 30 atm (~450 psi).



Figure 4: Mid-pressure Combustion Chamber for Photoignition Test

The mid-pressure combustion chamber for photoignition test up to about 30 atm (450 psi) of pressure with the ultrasonic fuel injector installed at the top of it. In this case the light source is located outside of the chamber against the lower back window (D=5 cm, L=2.5 cm) and the ignition capsule/torch sits inside the chamber and against the same window.

3.5 Improving Ignition Envelope

To improve the ignition characteristics, we considered adding mixtures of energetics to the gel capsule described in Section 3.4 [15]. We considered mixtures including additional fuels—Al₂O₃ NP and solid rocket fuel (SRF)—and additional oxidizers as described below. In all cases the photosensitive ingredient was CNT with 51% Fe content from Unidym Inc.

The Al₂O₃ NPs had a nominal size of 18 nm and were passivized in order to prevent them from oxidizing. SRF was specially formulated to produce a rapid combustion similar to a typical rocket fuel, while being non-explosive due to safety considerations. Commercially available model rocket fuel (MRF) used for hobby rocketry was also used for photoignition with similar results. The solid oxidizers are used in SRF in order to provide burning capability without air, but we use it in order to enhance the burning rate and the burning temperature of CNT.

Ignition characteristics of the mixtures were considered at atmospheric pressure and at elevated pressures. The chamber shown in Figure 4 was used for this series of experiments; the chamber was pressurized with either nitrogen, air or a combination of the two.

4.0 RESULTS AND DISCUSSION

4.1 Effect of Production Method

The two sets of SWCNT samples were tested for photo-ignition capability. The Unidym samples exhibited successful photo-ignition, comparable to that described in literature; however, the samples from Sigma Aldrich exhibited no photoignition from exposure to the highest level of flash that was available. A small reaction was obtained from the Sigma Aldrich material only after subjecting the sample to the focused beam of a 300W xenon arc lamp for approximately 30 seconds. Analyzing the differences in these two samples provides greater understanding of the mechanism by which photo-ignition is achieved.

Both sets of SWCNT samples were analyzed prior to and post reaction. Compositions of the samples, measured by EDS at several points and averaged, are given by weight percentage in Table 1. The post-ignition composition of Unidym samples suggests that some of the carbon content of the sample was lost as gaseous CO₂ or CO, while the Fe content of these samples was retained as iron oxide. The results for the post-reaction Sigma Aldrich material proved nearly identical to that of the pre-ignition. It is believed that the reaction observed was a small amount of amorphous carbon oxidizing and leaving the surface due to the heat of the focused beam.

Table 1: Elemental Composition by Weight of the SWCNT Samples as Recorded by EDS

Elements → Samples ↓	C (wt%)	O (wt%)	Fe (wt%)	Ni (wt%)	Y (wt%)
Unidym Pre-Ignition	49.67	0.70	49.64	N/A	N/A
Unidym Post-Ignition	27.19	1.47	71.10	N/A	N/A
Sigma Aldrich	32.60	0.31	N/A	58.76	9.04

Overall, the Unidym CNT samples, i.e. those containing iron, exhibited clear evidence of photoignition including visual, chemical, microscopic changes [13, 14]. The Sigma Aldrich samples, those containing nickel and yttrium, exhibited slight visual evidence of a potential reaction at very high heating but no chemical or microscopic evidence of a reaction [13].

Therefore, it is reasonable to conclude that the iron used in forming the nanotubes plays an important role in the photoignition.

4.2 Effect of Light Source and Compaction

We considered the effect of various aspects of the light source on photoignition. These parameters included wavelength band, pulse width, and overall energy. We observed that regardless of optical filter in use (i.e., the selected incident wavelength region), the minimum energy/pulse needed for the onset of ignition only depends on the pulse width of the Xe-flash unit. For the low light-energy setting (corresponding to a shorter pulse width of 0.2 ms) the MIE is mostly within 30-35 mJ/pulse; for the high light-energy setting (corresponding to a much longer pulse width of 7 ms) the MIE is about 80-95 mJ/pulse. More details on our results can be found in reference [14].

4.3 Photoignition beyond SWCNTs

We have investigated the photoignition properties of a number of nanoparticles and nano-energetic materials. The parameters of interest are MIE and burn temperature for different materials, as listed in Table 2. While we studied a wide variety of materials, Table 2 only includes materials that are well characterized and showed a consistent photoignition effect: a complete list of materials examined was given in Section 3.3 and may be found in reference [14]. The stated error figures in Table 2 are the measured statistical variations for the first four samples and they are the estimated uncertainty for the last three samples. We found that CNT samples with ~51% Fe content exhibited the most sensitive response to photoignition. We also observed interesting behavior in GO which prompted a more in-depth study of that material.

Table 2: MIE for Different Nanostructured Materials and their Corresponding Burn Temperatures

Nanoparticle Samples	Particle Size/ Smallest Dimensional Size	Min. Ignition Energy/area, Optical Fluence (mJ/cm ²)	Ignition/Burn Temperature* (°C)
CNT(51% Fe)	< 30 nm	64 ± 8	490 ± 30
CNT(18% Fe)	< 30 nm	182 ± 13	420 ± 50
Graphene Oxide Foam/Nano platelets	< 30 nm thick platelets	500 ± 60	370 ± 100
Al-nanoparticles	18 nm	290 ± 50	1100 ± 150
Fe, Carbon coated	~ 40 nm	220 ± 35	250 ± 30
Fe powder	~ 30 nm	150 ± 25	220 ± 30
Pd powder	~ 12 nm	530 ± 60	320 ± 40

*this is the temperature of a focused spot on the sample and may not be representative of the entire sample

We have found that the photo thermally initiated deflagration of GO can initiate liquid fuel ignition. GO readily disperses in alcohols, and with some chemical modification can disperse in other fuels as well [8]. The coupling of these two properties makes GO promising as a fuel additive and enticed us to investigate this photo thermally driven process further. We chose to focus on GO foam networks because the low-density networks of nanoscale GO

platelets serves two purposes: first, the surface to volume ratio of the platelets is increased, providing maximum surface area for energy absorption; second, thermally conductive pathways through which absorbed energy can diffuse are reduced, resulting in the enhancement of the photothermal effect. GO foam networks enable greater energy absorption and confinement can be achieved; as a result, more rapid and dramatic temperature increases can be achieved. We found the ease of ignition and reaction propagation in GO foams to be heavily dependent on the density of the foam. Denser GO foams ($> 50\text{mg/cm}^3$) were typically more difficult to ignite requiring several flashes at close range ($<1\text{ mm}$) in order to initiate a reaction. The reaction front then propagates through the material at a rate of 10 cm/sec . The lower density GO foams ($< 5\text{ mg/cm}^3$) was easier to ignite with $<0.5\text{ J/cm}^2$ optical fluence, but they do not produce enough heat via deflagration to sustain a reaction front, and, thus, the reaction front was not self-propagating [8].

Microscopic differences were observed between flashed samples in an Ar environment compared to those in the open air. SEM images of the open air samples look as though they contain amorphous carbon at the edges while Ar samples exhibited a fine expanded structure (see Figure 5 and reference 8). We attribute this amorphous carbon to secondary burning of the newly formed graphitic carbon in atmospheric oxygen after the removal of H_2O and CO_2 from the primary deflagration reaction [8].

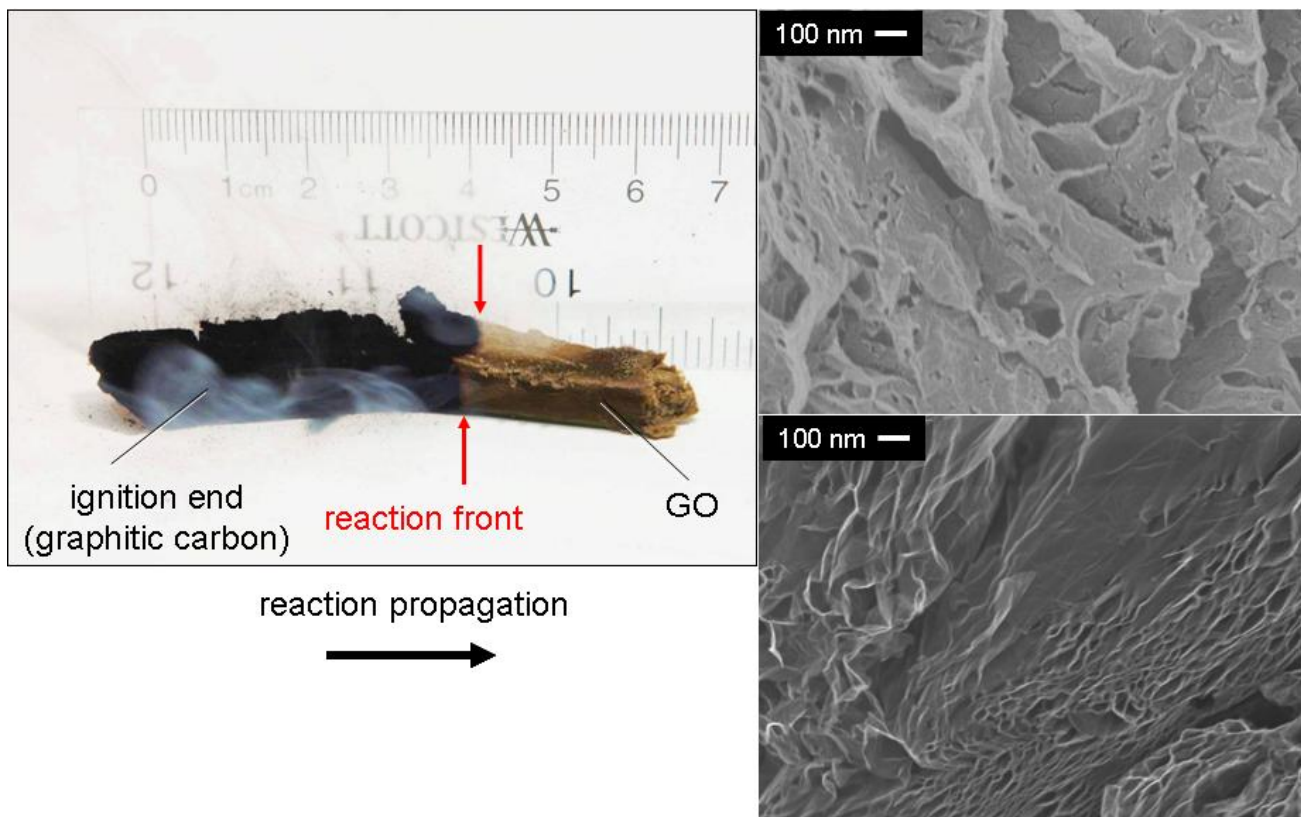


Figure 5: Photographic Image of a 15 mg/ml GO Foam Sample after Photoignition

A photographic image of a 15 mg/ml GO foam sample after photoignition on the left shows the propagation of the reaction front from left to right. GO foams flashed in open atmosphere typically burn in atmospheric oxygen after deflagration yielding amorphous carbon at the edges as shown in the SEM image (b). If flashed under Ar atmosphere, the GO foams do not burn in atmospheric oxygen after release of CO_2 and H_2O resulting in a more pure exfoliated sample (c) (after reference [8]).

4.4 Ignition of Fuel Sprays

Our first observation when attempting to ignite a fuel spray with CNTs was that when the photo-ignitable mixture was placed close to the fuel spray, it became more difficult to ignite it as it became wet with the fuel. Therefore, we came up with encapsulation of CNTs in order to keep the samples dry. If there were enough CNTs in the capsule then the gaseous byproducts of the photoignition (mostly CO₂ or CO) would pressurize the capsule beyond 30 psi and it would rupture and release its burning contents in the vicinity of the fuel spray, causing the spray to ignite with a reasonable rate of success, typically better than 90%. It was found that a small hole, ~ 2mm in diameter, made at the end of the capsule results in rapid discharge of a combination of hot gas, flame, and burning particles that extends 15-30 cm away from the ignition capsule. This is referred to as a photoignition/ignition torch and it has exhibited an improved rate of success in the fuel spray ignition by discharging of a longer lasting jet of burning particles.

At atmospheric pressure, a typical photoignition torch burned up to ~0.5 second depending on the amount of fuel in the capsule. As the ambient pressure is increased beyond ~10 atm, the burn rate gradually increases and the burn duration decreases, so that at ~30 atm the burn duration is no more than half of what it is at 10 atm for most CNT fuel mixtures. Despite the change in torch characteristics, we were still able to ignite fuel sprays at elevated pressures and at cryogenic temperatures [15, 16].

4.5 Improving Ignition Envelope

While we were able to ignite a fuel spray with a photoignition torch that contained only CNTs, such an ignition torch exhibited a number of drawbacks. These are due to the fact that CNTs do not burn long and hot enough and the amount of gas generated may not be sufficient for an effective ignition torch in many applications. To overcome these limitations, we considered adding different energetic materials to the capsule along with the photosensitive CNTs. A typical ignition torch has a total mass of no more than 200 mg, of which about 130 mg is due to the empty capsule and the rest is the CNT fuel mixture, only a small fraction of it is CNTs, typically 1-3 mg, out of the total fuel that is 30-70 mg. The encapsulated CNT fuel mixture typically burns for 200-500 ms at atmospheric pressure and for 50-100 ms at about 50 atm. Figure 6 shows an example of the photoignition of a fuel spray that was achieved by an ignition capsule that was directly attached on the flash of a disposable camera.

Numerous additives were considered, each serving different purposes. The function of CNT is to provide photoignition at a low light level (less than 0.1 J/cm^2), while it produced substantial amount of gas to pressurize the capsule. The solid oxidizer serves to speed up the propagation of ignition to other solids as well as to increase the duration of the burning beyond 200 ms; it also burns at a higher temperature (800-1200 K). For the solid oxidizer, potassium permanganate (KMnO_4) and boron-potassium nitrate (BKNO_3) were used. While technically BKNO_3 is not merely an oxidizer, but a mix of fuel (boron) and oxidizer (KNO_3), its purpose here is mainly as an oxidizer. The role of the Al_{NP} is to rapidly increase the temperature ($>1500\text{K}$) in order to ignite the SRF [15].

Different proportions of three ingredients produced an igniter with different ignition properties such as ignition temperature, duration, pressure ramp up and ignition delay. Table 3 shows examples of ingredients of different ignition capsules along with the weight percentage of each of the ingredients in the capsule. Comments about the relative advantages and possible disadvantages of each specific mixture are also stated in Table 3. The best photoignition torch for igniting of cryogenic H_2/O_2 cryogenic coaxial spray within 20-50 atm pressure has been generated by samples 7 through 10 in Table 3 respectively. More details of this aspect of our work may be found in reference [15, 16].

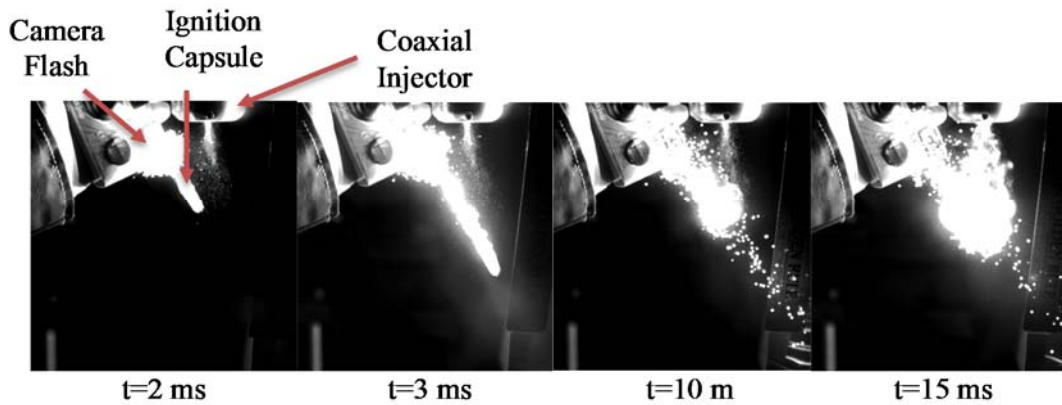


Figure 6: Photoignition of Hexane+Acetone (50% each)

Photoignition of Hexane+Acetone (50% each) in a sequence of images, where $t=0$ indicates the peak of the flash. In this case gaseous O_2 was introduced in a coaxial flow at a rate of 7 Lit/min with a swirl motion in order to produce an effective fuel and oxidizer mixing. The liquid fuel was injected at a rate of about $3 \text{ cm}^3/\text{min}$ through a programmable syringe pump. These images were captured at 2000 FPS and exposure time of $490 \mu\text{s}$.

Table 3: Ingredients for a Photoignition Torch for Different Chamber Pressures

CNT, main Photoignition Agent (Wt %)	Fuel Al₂NP 18/80 nm (Wt%)	Fuel SRF (Wt%)	Oxidizer BKNO₃ (Wt%)	Oxidizer KMnO₄ (Wt%)	Observations and Comments On the Relative Effects of Additives
Sample 0 100%					Short burn duration & low burn Temp. (~800K)
Sample 1 10%			90%		Improved ignition reliability & burn Temp.
Sample 2 10%				90%	Reliable ignition only ≥ 10 atm
Sample 3 ~3%		~97%			Unreliable ignition of SRF associated with a long ignition delay (ratio doesn't matter)
Sample 4 3%	7-12%	85-90%			More reliable ignition, burns at higher T & is more energetic than samples 2 & 3
Sample 5 3%	7%	45%		45%	Less reliable ignition than the above unless the chamber Pressure ≥ 10 atm
Sample 6 3%	7%	50%	40%		Improved flash sensitivity & ignition + generate a lot of gas & smoke
Sample 7 1%	9%	80%	10%		Best ignition sensitivity, reliability & burn duration for chamber Pressure ≥ 7 atm
Sample 8 2%	8%	70%		20%	Comparable to sample 7 only for chamber Pressure ≥ 15 atm
Sample 9 2%	8%	70%	20%		Improved ignition reliability and burn duration
Sample 10 1%	15%	75%	9%		As good as the above at atmospheric pressure, but burns too fast ≥ 15 atm

5.0 CONCLUSIONS

We have shown that CNTs can be easily ignited in distributed manner with a low-level Xenon arc pulsed source such as a camera flash. The production method of the CNTs plays a role in their ability to be ignited by a flash suggesting that iron may play a role in this phenomenon. We studied minimum ignition energy and found that the pulse width played an important role in determining the minimum ignition energy. The shorter the light source pulse duration is the lesser need for the minimum amount of energy necessary to bring about ignition of the as-produced samples of the SWCNTs. Other aspects of the light, such as wavelength band, did not alter the ignition energy. As expected, samples with a higher degree of compaction require considerably higher energy per pulse for ignition. Moreover, the ignition process is very gradual and less well-defined in moderately- and heavily- compacted samples. We found that this problem is dramatically reduced in an oxygen-rich environment. The photo-acoustic effect measured via a microphone mostly correlates with the observed photo ignition characteristics. Photoignition of different fuel sprays was achieved through photoignition of encapsulated CNTs, which injects burning particles into the path of the spray. Encapsulation was required because once wet the nanotubes did not exhibit photoignition effect. The mixture within the capsule can be tailored to improve ignition characteristics, and we examined the effects of several additives. Through tailoring this mixture, we also proved that we could ignite SRF using a mixture of photosensitive CNTs and aluminum nanoparticles. Overall, this project demonstrated an improved new igniter concept which is compact, robust, and stable, while it requires minimal energy input. We are seeking a patent on our concept, which we have titled PITCH, PhotoIgnition TorCH [1].

6.0 RECOMMENDATIONS

PITCH as described can be used for high pressure ignition of liquid and solid rockets as well as initiation of other combustion processes that require a high energy and distributed ignition method. We recommend the following possible improvements and demonstration in the future:

Further optimization of PITCH

- Modification of SFMs for control of ignition energy, burn duration, and burn properties
- Managing ignition transient effects through SFM formulation
- Effects of ambient oxygen on the photoignition process
- Optimizing for specific fuels, e.g. M315E monopropellant

Expand PITCH for space/satellite applications

- Study of long term stability of different SFM formulations in space environment
- Modification for application in vacuum
- Control of ignition duration and burn properties for space vehicles
- Ruggedization for long time survival in space environment
- A design with many ignition capsules and a few drive electronics for multiple ignition events

Photoignition agents as liquid fuel additives:

- Micro encapsulation of SFM in order to use it as an additive for liquid fuels
- Use of the above in specialized fuel injectors in order to achieve distributed ignition in larger rocket engines

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

Al_NP	aluminum nanoparticles
Ar	argon
atm	atmospheric pressure
BKNO ₃	boron potassium nitrate
CNT	carbon nanotube (as-produced i.e. unpurified SWCNT)
EDS	Energy Dispersive Spectroscopy
Fe	iron
FPS	frames per second
GO	graphene oxide
KMnO ₄	potassium permanganate
MIE	minimum ignition energy
MRF	model rocket fuel
Ni	nickel
OD	outer diameter
Pd	palladium
PITCH	PhotoIgnition TorCH
psi	pounds per square inch
SEM	scanning electron microscopy
SFM	solid fuel mixture
SRF	solid rocket fuel
SWCNT	single-wall carbon nanotube (also abbreviated as SWNT in the literature)
Wt %	percent weight
Xe	xenon
Y	yttrium

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